

XVII International Colloquium on Mechanical Fatigue of Metals (ICMFM17)

The role of microstructure in fatigue crack initiation and propagation in 9-12Cr ferritic-martensitic steels

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Abstract

The present paper presents low-cycle fatigue results about cyclic behaviour, the evolution of the dislocation structure and the nucleation and propagation of microstructural cracks in commercial ferritic-martensitic steel AISI 410.

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Selection and peer-review under responsibility of the Politecnico di Milano, Dipartimento di Meccanica

Keywords: Ferritic-martensitic steel, LCF, microstructure, microcrack nucleation

1. Introduction

Previous low-cycle fatigue studies on 9-12Cr ferritic-martensitic steels showed that cyclic softening occurs due to microstructural instability over a wide range of temperatures [1-5]. This effect could become a serious engineering problem affecting creep, swelling and segregation phenomena during irradiation. Cyclic softening of 9-12Cr steels is associated with instability of the dislocation structure over the entire range of temperatures and, with the coarsening of carbides at high temperatures.

Nowadays, the softening stage in 9-12Cr steels is clearly associated with the increase of the subgrain size regardless of the temperature. Moreover, the softening has been at least partially explained by lath and sub-grain boundary elimination [6].

The aim of this paper is to correlate the microstructural evolution with microcracks nucleation and propagation

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2. Experimental procedure

The material considered in this study was the commercial AISI 410 with chemical composition in weight percent of: C: 0.11; Si: 0.47; Mn: 0.7; Ni: 0.38; Cr: 13; Fe: balance. Before testing, the steel was austenitized at 1000°C during 0.5 hs and tempered at 760°C during 1.5hs. After each heat treatment the steel was air cooled. The resulting yield stress is 550MPa.

The microstructure of the steel consists of a tempered martensitic lath structure composed of small subgrains of about 0.5 μm in diameter with a substantial dislocation structure. M_{23}C_6 carbides of about 0.2 μm in diameter were distributed preferentially along laths, forming long chains of particles, and along prior austenitic grain boundaries. It is interesting to note that the high dislocation density produced during the quenching of the steels remains after tempering.

In order to analyze the cyclic behavior of the steel and the dislocation structure developed during cycling, low-cycle fatigue tests were performed on solid specimens with a cylindrical gauge section 77mm in length and 8.8 mm in diameter. Additionally, studies on micro-cracks initiation and growth during fatigue were carried out on slightly shallow-notched cylindrical specimens [7]. The notch focuses the fatigue damage in the zone of observation, (stress concentration factor is 1.06 at the notch tip). Mechanical and electrolytical polish was given to the surface of the shallow notch to improve the observation of micro-crack nucleation and growth. The central part of the notch was monitored during the test using a powerful optical system consisting of a CCD camera JAI mod. CM-140MCL with an objective of 50X, $\pm 1\mu\text{m}$ FD and 13mm WD and a 12X ultra zoom.

The fatigue tests were performed in both cases using a triangular wave at a strain range of $\Delta\epsilon_p = 0.2\%$ with a total strain rate $\dot{\epsilon} = 3 \times 10^{-3} \text{ s}^{-1}$. Transversal disks were cut from the gauge length of the specimen and then electrolytically thinned for TEM observations.

3. Results and discussion

The following results are part of an extended research which is being carried out in 9-12Cr ferritic-martensitic steels regarding cyclic behavior, microstructure development and microcrack nucleation and propagation. The reduced activated ferritic-martensitic EUROFER97, and commercial AISI 410 and 420 are selected steels for this investigation.

The behavior of AISI410 during plastic strain-controlled tests, performed at room temperature has been analyzed. Under these test conditions, the steel show, after the first few cycles, a cyclic softening that continues up to failure. Fig. 1 shows this behavior in comparison with the modified 9-12Cr EUROFER 97, already reported in previous papers [1-3]. It is interesting to note the close behavior of both materials not only in the cyclic behavior but also in the microstructural development [2-3].

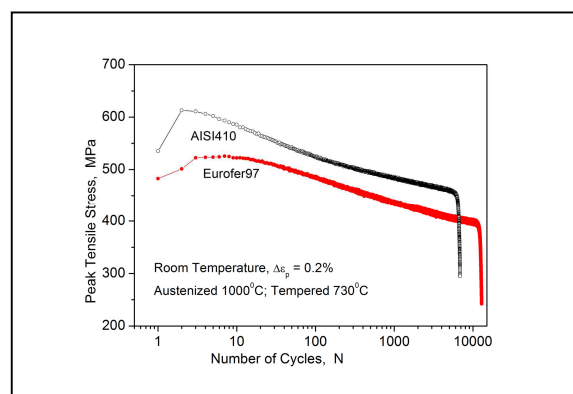


Fig. 1. Cyclic deformation behavior of AISI 410 steel and compare with the modified ferritic martensitic steel EUROFER97.

The stability of normalized and tempered 9-12Cr modified ferritic-martensitic steels during subsequent annealing times up to 1100 hours at 550°C is a well-known result [8]. However, this apparent microstructural stability could be destabilized under cyclic strain conditions as was already shown [1] in modified 9Cr-1Mo steels. The apparently stable lath martensite structure is strongly unstable under cyclic conditions being gradually replaced by the development of a cell structure. As it is observed in Fig. 2 a-b, the original parallel martensitic laths are partitioned in equiaxed subgrains of larger diameter with a clearer interior. As well, it is important to remark in certain zones the refinement as well as dissolution of the subgrain walls leaving the former precipitates, encircled in Fig. 2 c.

Previous results [9] show a close resemblance between the cyclic and microstructural behavior of AISI 410 steel with EUROFER 97 steel. Nevertheless, the AISI 420 steel behavior is not so close with the former ones. According to Armas et al [1], the martensite start temperature M_s is a defining parameter in the lath feature after tempering and hence in its evolution after fatigue.

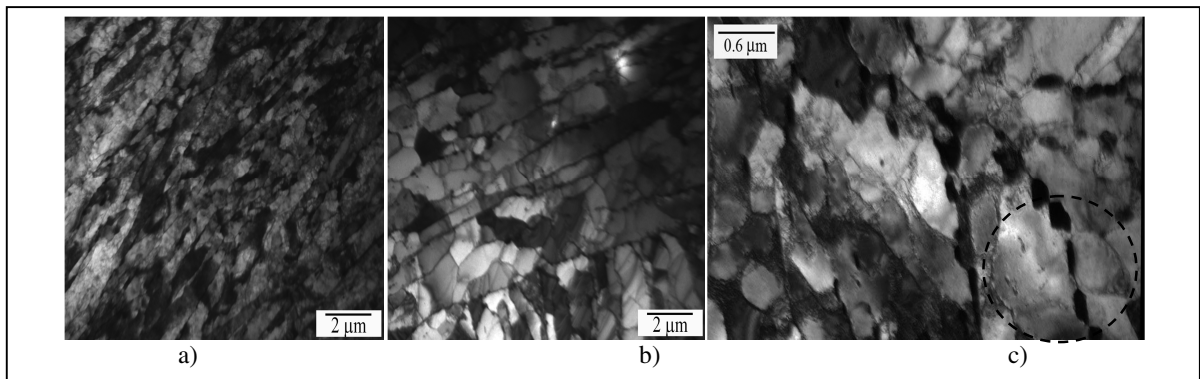


Fig. 2. (a) Initial tempering microstructure of AISI 410; (b) lath structure turn into subgrain structure after cycling; c) detailed structure.

Fig. 3 shows the in situ observation of specimens subjected to LCF in the present mechanical conditions. Fig.3b). reveals that the first deformation lines appear at about 50 cycles along lath boundaries oriented about 45° with respect the tensile axis (vertical axis) After a certain number of cycles, the lines intensify and turn into bands, Fig. 3 c). Finally, cracks nucleate on these slip marks, Fig. 3d).

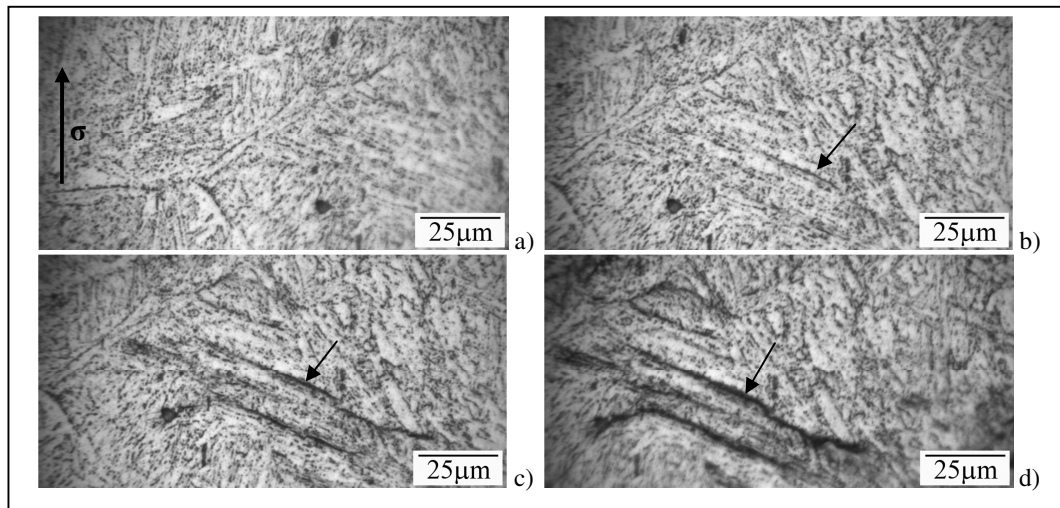


Fig. 3. In situ optical micrographs of AISI 410 taken during the fatigue test at: a) 0 cycles; b) 10 cycles; c) 60 cycles; d) 160 cycles.

As it was observed during in situ micrographs, for the present tempering martensite microstructure, a great portion of the fatigue life is spent nucleating and growing fatigue microstructural cracks. A great number of these cracks nucleate on slip markings in the growth path of the dominant crack which results in specimen failure. This concept means that microstructural cracks growth individually as Stage I within former austenitic grains, cross one or two grain boundaries and finally coalesce in the macrocrack.

In order to address fatigue damage in martensitic steels, it is necessary to understand the mechanisms that facilitate crack initiation. Slip irreversibility occurs in materials and accumulate during fatigue loading. At the defect level, the irreversibility is a result of dislocation pile-up, annihilation or cross-slipping. Boundaries such as grain boundary or inclusion-matrix phase boundary contribute also with slip irreversibility. These slip irreversibilities are the early signs of damage during cyclic loading. The dislocations subsequently form low-energy stable structures as a mean to accommodate the irreversible slip processes and modify the dislocation density during cyclic forward and reverse loading. The result is strain localization, precursor to crack initiation, in a small region within the materials.

Inclusions and precipitates are special defects that can initiate cracks due to different factors such as the slip characteristic of the matrix, the relative strength values of the matrix and the inclusion, the strength of the matrix-inclusion interface and environment factors.

During cycling 9-12Cr steels, including the modified steels, reduce the free dislocation density and produce the refinement of the cell walls, leaving, as it is observed in Fig. 2c), larger dislocation mean free path for dislocation motion. Depending on the structure relationship between the matrix and precipitates, these interfaces can be the weakest sites of a material. Matrix and precipitates may raise the mechanical stress in the vicinity of the interface during cyclic loading causing, eventually, interfacial crack initiation. Of course the level of this stress depends strongly on the size of the inclusion. Normally, small nonmetallic inclusions are considered harmless for materials of low purity. In the present steel, second phase particles are rather small in size but they are located in large chain of precipitates producing a strong barrier against dislocation motion. Therefore, this combination of factors could be the first step to explain why microstructural cracks initiate at lath boundaries where chains of precipitates are located.

4. Conclusions

In the present commercial ferritic-martensitic steel AISI 410, the correlation between microstructural evolution and microcracks nucleation showed that the interface matrix-precipitate, when they are aligned forming a chain, can be a probable crack nucleation site.

Acknowledgements

This work was supported by Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET).

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